
Advanced Electric Power Generation Fluidized-Bed Combustion

McIntosh Unit 4A PCFB Demonstration Project

Participant

City of Lakeland, Lakeland Electric

Additional Team Members

Foster Wheeler Corporation—supplier of pressurized circulating fluidized-bed (PCFB) combustor and heat exchanger; engineer

Siemens Westinghouse Power Corporation—supplier of hot gas filter, gas turbine, and steam turbine

Location

Lakeland, Polk County, FL (Lakeland Electric's McIntosh Power Station, Unit No. 4)

Technology

Foster Wheeler's PCFB technology integrated with Siemens Westinghouse's hot gas particulate filter system (HGPFS) and power generation technologies

Plant Capacity/Production

137-MWe (net)

Coal

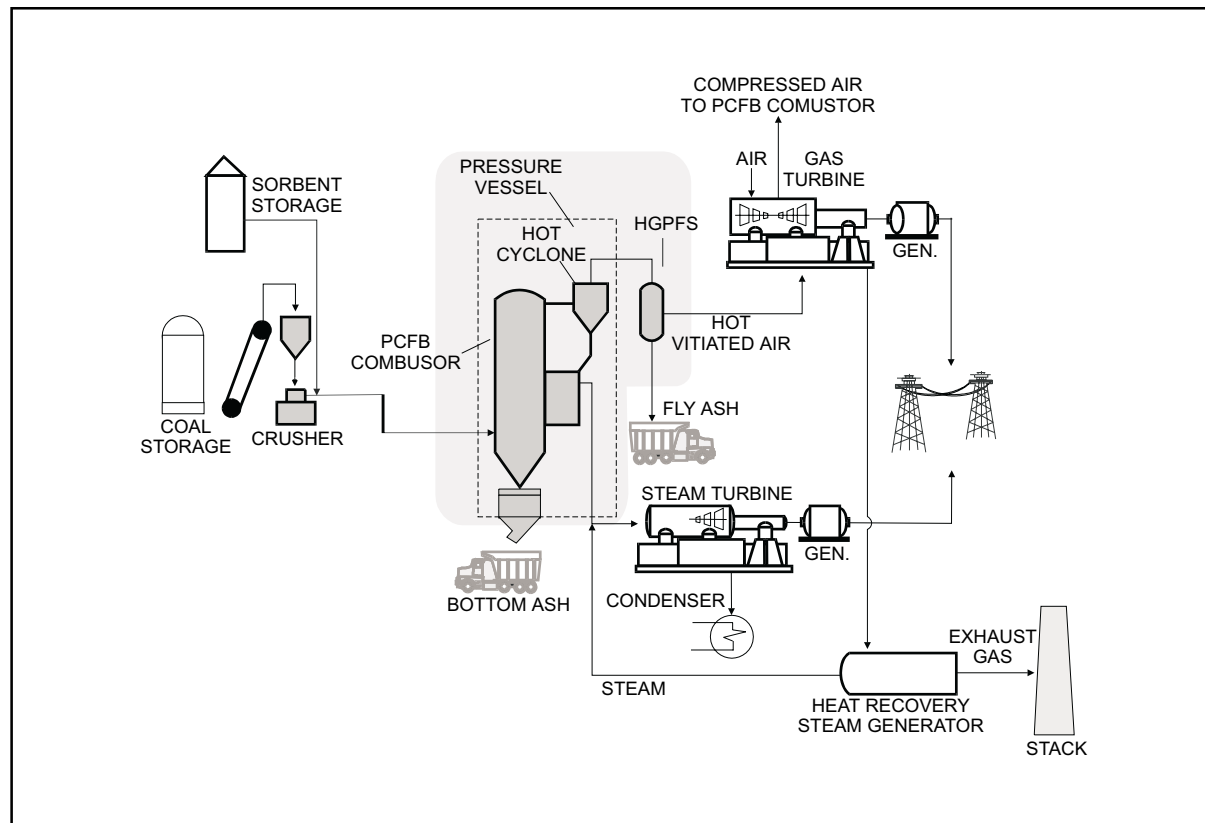
Eastern Kentucky and high-ash, high-sulfur bituminous coals

Project Funding

Total project cost	\$186,588,000	100%
DOE	93,252,864	50
Participant	93,335,136	50

Project Objective

To demonstrate Foster Wheeler's PCFB technology coupled with Siemens Westinghouse's ceramic candle type HGPFS and power generation technologies, which represent a cost-effective, high-efficiency, low-emissions means of adding generating capacity at greenfield sites or in repowering applications.



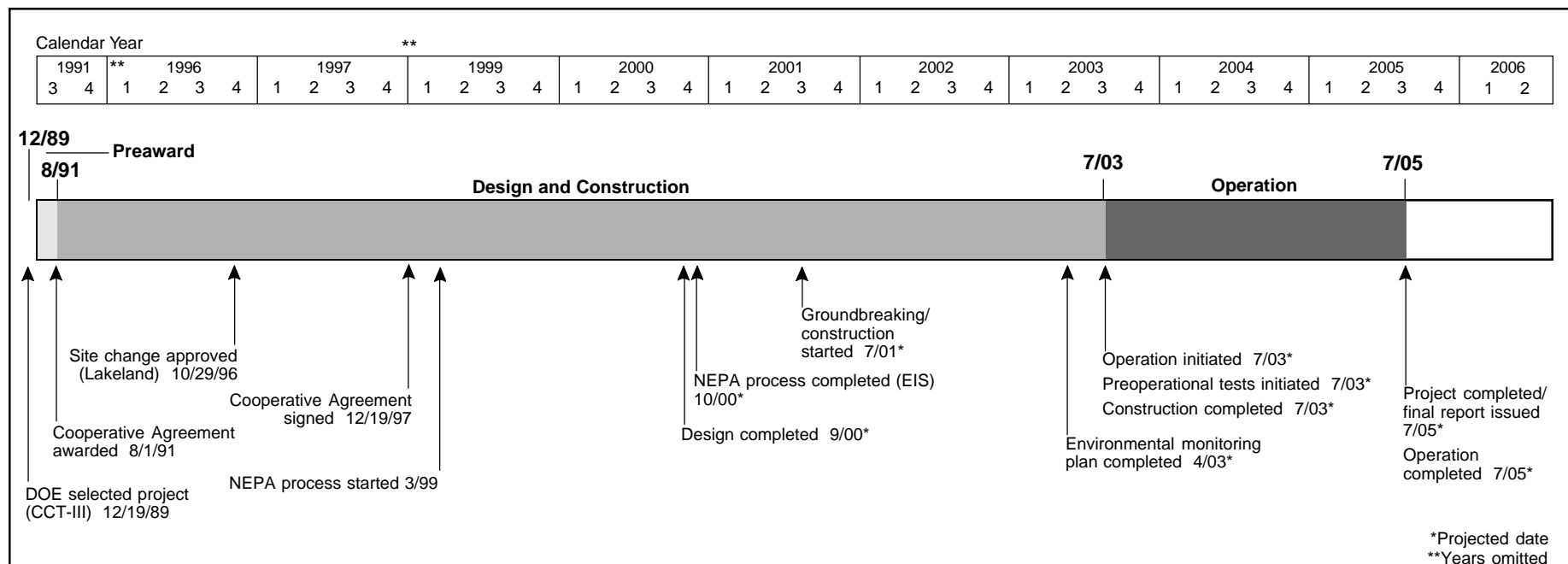
Technology/Project Description

The project resulted from a restructuring of the DMEC-1 PCFB Demonstration Project awarded under CCT-III. In the first of the two Lakeland Electric projects, McIntosh Unit No. 4A is being constructed with a PCFB combustor adjacent to the existing Unit No. 3 (see also McIntosh Unit 4B Topped PCFB Demonstration Project).

Coal and limestone are mixed and fed into the combustion chamber. Combustion takes place at a temperature of approximately 1,560–1,600 °F and a pressure of about 200 psig. The resulting flue gas and fly ash leaving the combustor pass through a cyclone and ceramic candle type HGPFS where the particulates are removed. The hot gas leaving the HGPFS is expanded through a Siemens V64.3 gas turbine. The gas inlet temperature of less than 1,650 °F allows for a simplified turbine shaft and blade-

cooling system. The hot gas leaving the gas turbine passes through a heat recovery steam generator (HRSG). Heat recovered from both the combustor and HRSG is used to generate steam to power a reheat steam turbine. Approximately 5–10% of the gross power is derived from the gas turbine, with the steam turbine contributing the balance.

The project also includes an atmospheric fluidized-bed unit that can be fired on coal or char from the carbonizer and will replace the PCFB unit during times of PCFB unavailability, allowing various modes of operation.



Project Status/Accomplishments

On December 19, 1997, a Cooperative Agreement modification was signed implementing the project restructuring from DMEC-1 to the City of Lakeland. The Lakeland City Council gave approval in April 1998 for the 10 year plan of Lakeland Electric (formerly Department of Electric & Water Utilities), which included this project. The project schedule anticipates the start of commercial operation of the PCFB (McIntosh 4A) in 2003. In parallel with the first two years of operation of the PCFB, the design, fabrication, and construction of the topped PCFB technology (McIntosh 4B) will occur, with a planned start of operation in 2005. Negotiations continue between Lakeland and Foster Wheeler on the Engineer-Procure-Construct proposal for the technology island.

The Notice of Intent to prepare an EIS was published in the Federal Register on March 26, 1999. The public scoping meeting was held April 13, 1999, in Lakeland, Florida.

Recent efforts focused on testing the HGPFS, which is critical to system performance. Silicon carbide and alumina/mullite candle filters proved effective under conditions simulating those of the demonstration unit. At both 1,550 °F and 1,400 °F, the candle filters performed for over 1,000 hours at design levels without evidence of ash bridging or structural failure. Three new oxide-based candle filters showed promise as well and will undergo further testing because of the potential for reduced cost and operation at higher temperatures.

Commercial Applications

The project serves to demonstrate the PCFB technology for widespread commercial deployment in post-2000. The project will include the first commercial application of hot gas particulate cleanup and one of the first to use a non-ruggedized gas turbine in a pressurized fluidized-bed application.

The combined-cycle PCFB system permits the combustion of a wide range of coals, including high-sulfur

coals, and would compete with the pressurized bubbling-bed fluidized-bed system. PCFB can be used to repower or replace conventional power plants. Because of modular construction capability, PCFB generating plants permit utilities to add economical increments of capacity to match load growth or to repower plants using existing coal- and waste-handling equipment and steam turbines. Another advantage for repowering applications is the compactness of the process due to pressurized operation, which reduces space requirements per unit of energy generated.

The projected net heat rate for the system is approximately 9,480 Btu/kWh (HHV), which equates to an efficiency greater than 36%. Environmental attributes include *in-situ* sulfur removal of 95%, NO_x emissions less than 0.3 lb/10⁶ Btu, and particulate matter discharge less than 0.03 lb/10⁶ Btu. Solid waste will increase slightly as compared to conventional systems, but the dry material is readily disposable or potentially usable.

McIntosh Unit 4B Topped PCFB Demonstration Project

Participant

City of Lakeland, Lakeland Electric

Additional Team Members

Foster Wheeler Corporation—supplier of carbonizer; engineer

Siemens Westinghouse Power Corporation—supplier of topping combustor and high-temperature filter

Location

Lakeland, Polk County, FL (Lakeland Electric's McIntosh Power Station, Unit No. 4)

Technology

Fully integrated second-generation PCFB technology with the addition of a carbonizer island that includes Siemens Westinghouse's multi-annular swirl burner (MASB) topping combustor

Plant Capacity/Production

103-MWe (net) addition to the 137-MWe (net) McIntosh 4A project

Coal

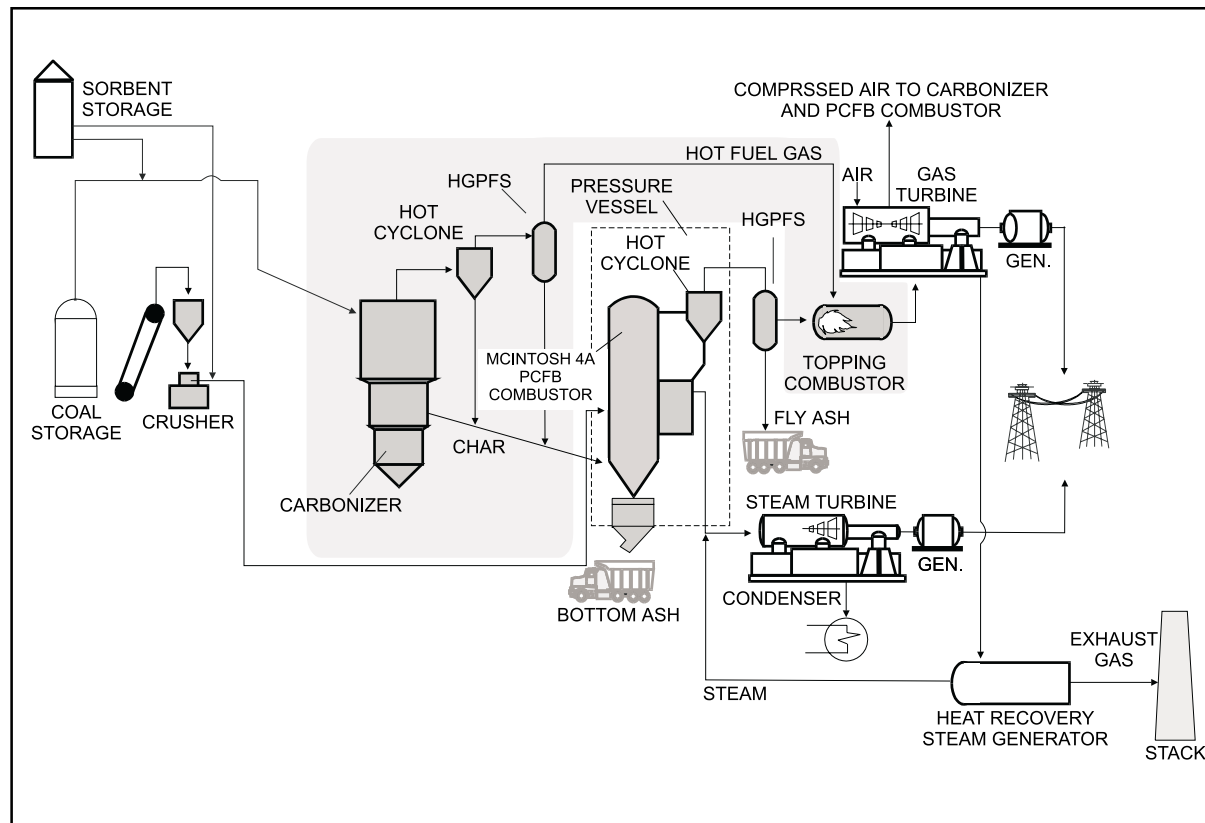
Eastern Kentucky and high-ash, high-sulfur bituminous coals

Project Funding

Total project cost	\$219,635,546	100%
DOE	109,608,507	50
Participant	110,027,039	50

Project Objective

To demonstrate topped PCFB technology in a fully commercial power generation setting, thereby advancing the technology for future plants that will operate at higher gas turbine inlet temperatures and will be expected to achieve cycle efficiencies in excess of 45%.

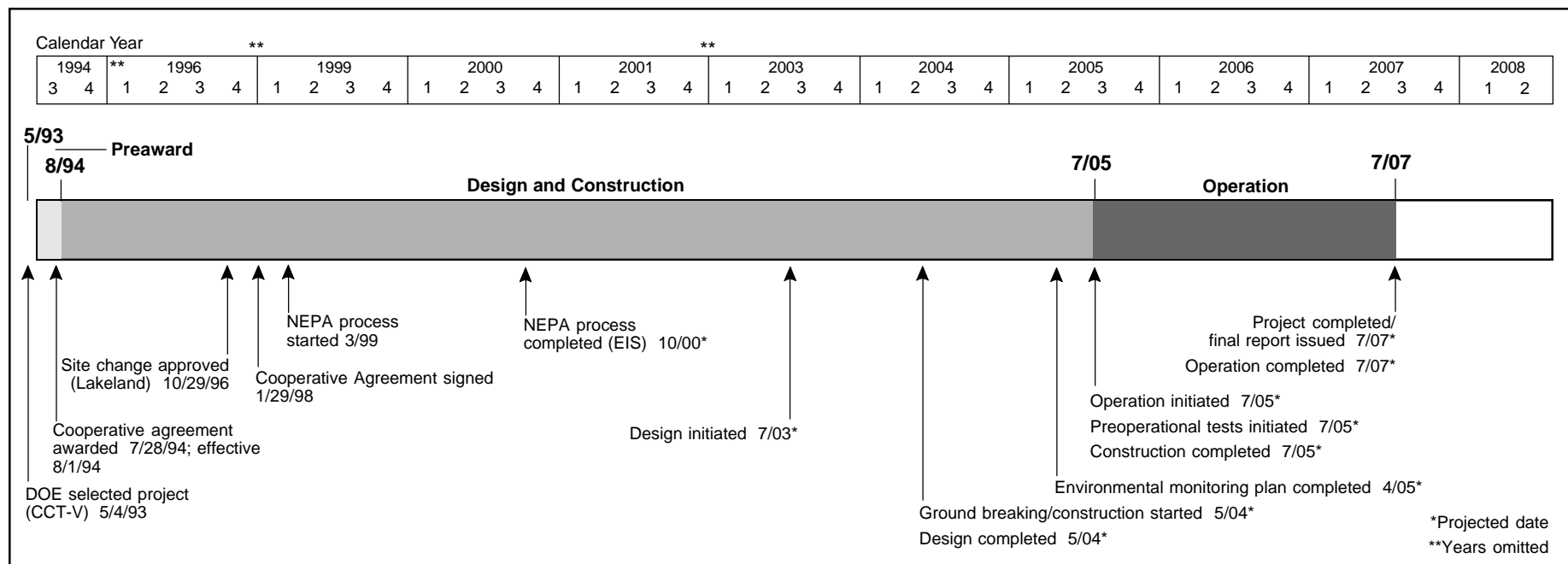


Technology/Project Description

The project involves the addition of a carbonizer island to the PCFB demonstrated in the McIntosh 4A project. Dried coal and limestone are fed via a lock hopper system to the carbonizer with part of the gas turbine discharge air. The coal is partially gasified at about 1,750–1,800 °F to produce syngas and char solids streams. The limestone is used to absorb sulfur compounds generated during the mild gasification process. After cooling the syngas to about 1,200 °F, the char and limestone entrained with the syngas are removed by a hot gas particulate filter system (HGPFS). The char and limestone are then transferred to the PCFB combustor for complete carbon combustion and limestone utilization. The hot, cleaned, filtered syngas is then fired in the MASB topping combustor to raise the turbine inlet temperature to approximately 2,350 °F. The gas is expanded through the turbine, cooled in a heat

recovery steam generator, and exhausted to the stack. The net impact of the addition of the topping cycle is an increase in both power output and efficiency. The coal and limestone used in McIntosh 4B are the same as those used in McIntosh 4A.

The 240-MWe (net) plant is expected to have a heat rate of 8,406 Btu/kWh (40.6% efficiency, HHV). The design SO₂ capture efficiency rate is 95%. Particulate and NO_x emissions are expected to be 0.02 lb/10⁶ Btu and 0.17 lb/10⁶ Btu, respectively. In the final configuration, the gas turbine will produce 58 MWe and the steam turbine will produce 207 MWe, while plant auxiliaries will consume about 25 MWe.



Project Status/Accomplishments

The project resulted from a restructuring of the Four Rivers Energy Modernization Project awarded under the fifth solicitation. The Four Rivers project was to demonstrate the integration of a carbonizer (gasifier) and topping combustor (topping cycle) with the PCFB technology. By using a phased approach, Lakeland Electric will be able to demonstrate both PCFB (McIntosh 4A) and topped PCFB (McIntosh 4B) technologies at one plant site.

On January 29, 1998, a Cooperative Agreement modification was signed implementing the project restructuring from Four Rivers Energy Partners to the City of Lakeland. The Lakeland City Council gave approval in April 1998 for the 10 year plan of Lakeland Electric (formerly Department of Electric & Water Utilities), which included this project. In parallel with the first two years of operation of the PCFB (McIntosh 4A), the design, fabrication, and construction of the topped PCFB technology will take place. Start of operation is planned for late 2005. Negotiations continue between Lakeland and Foster Wheeler on the Engineer-Procure-Construct

Advanced Electric Power Generation

proposal for the technology island.

The Notice of Intent to prepare an EIS was published in the Federal Register on March 26, 1999. The public scoping meeting was held April 13, 1999, in Lakeland, Florida.

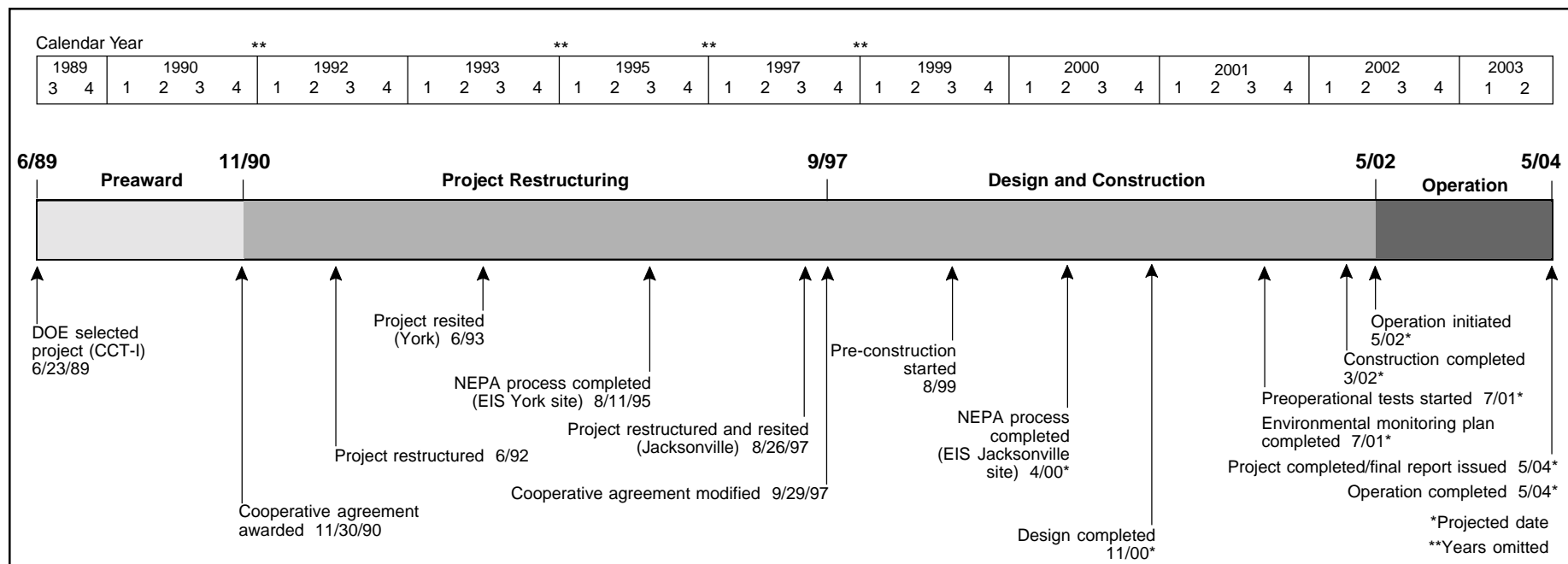
Recent efforts focused on testing the HGPFS, which is critical to system performance. Silicon carbide and alumina/mullite candle filters proved effective under conditions simulating those of the demonstration unit. At both 1,550 °F and 1,400 °F, the candle filters performed for over 1,000 hours at design levels without evidence of ash bridging or structural failure. Three new oxide-based candle filters showed promise as well. These will undergo further testing because of the potential for reduced cost and operation at higher temperatures.

Commercial Applications

The commercial version of the topped PCFB technology will have a greenfield net plant efficiency of 45% (which equates to a heat rate approaching 7,500 Btu/kWh, HHV). In addition to higher plant efficiencies, the plant

will (1) have a cost of electricity that is projected to be 20% lower than that of a conventional pulverized-coal-fired plant with flue gas desulfurization, (2) meet emission limits allowed by New Source Performance Standard (NSPS), (3) operate economically on a wide range of coals, and (4) be amenable to shop fabrication. The benefits of improved efficiency include reduced cost for fuels and a reduction in CO₂ emissions.

The commercial version of the topped PCFB technology has other environmental attributes, which include *in-situ* sulfur retention that can meet 95% removal, NO_x emissions that will meet or exceed NSPS, and particulate matter discharge of approximately 0.03 lb/10⁶ Btu. Although the system will generate a slight increase in solid waste compared to conventional systems, the material is a dry, readily disposable, and potentially usable material.



Project Status/Accomplishments

The project was successfully resited to Jacksonville, Florida after York County Energy partners and Metropolitan Edison Company terminated activities on the ACFB in September 1996. On August 26, 1997, DOE approved the transfer of the ACFB clean coal project from York, Pennsylvania to Jacksonville, Florida. On September 29, 1997, DOE signed a modified cooperative agreement with JEA to cost-share refurbishment of the first (Unit No. 2) of two units at Northside Generating Station.

A Public Scoping Meeting on the Environmental Impact Statement (EIS) was held on December 3, 1997, at the Northside Station. The public hearing on the draft EIS was held on September 30, 1999. The closing date on written public comments was October 15, 1999.

The project, currently in design, moves atmospheric fluidized-bed combustion technology to the larger sizes of utility boilers typically considered in capacity additions and replacements. The nominal 300-MWe demonstration unit in the JEA project will be more than double the size of the Nucla unit (110-MWe). Features include an inte-

grated recycle heat exchanger (INTREX™) in the furnace, steam-cooled cyclones, a parallel pass reheat control, an SO₂ polishing scrubber, and a fabric filter for particulate control. Expected environmental performance is 0.17 lb/10⁶ Btu for SO₂ (98% reduction), 0.11 lb/10⁶ Btu for NO_x, and 0.017 lb/10⁶ Btu for total particulates (0.013 lb/10⁶ Btu for PM₁₀).

Commercial Applications

ACFB technology has good potential for application in both the industrial and utility sectors, whether for use in repowering existing plants or in new facilities. ACFB is attractive for both baseload and dispatchable power applications because it can be efficiently turned down to 25% of full load. Coal of any sulfur or ash content can be used, and any type or size unit can be repowered. In repowering applications, an existing plant area is used, and coal- and waste-handling equipment as well as steam turbine equipment are retained, thereby extending the life of a plant.

In its commercial configuration, ACFB technology offers several potential benefits when compared to conven-

tional pulverized coal-fired systems: lower capital costs; reduced SO₂ and NO_x emissions at lower costs; higher combustion efficiency; a high degree of fuel flexibility (including use of renewable fuels) and dry, granular solid material that is easily disposed of or potentially salable.

Tidd PFBC Demonstration Project

Project completed.

Participant

The Ohio Power Company

Additional Team Members

American Electric Power Service Corporation—
designer, constructor, and manager

The Babcock & Wilcox Company—technology supplier
Ohio Coal Development Office—cofunder

Location

Brilliant, Jefferson County, OH (Ohio Power Company's
Tidd Plant, Unit No. 1)

Technology

The Babcock & Wilcox Company's pressurized fluidized-bed combustion (PFBC) system (under license from ABB Carbon)

Plant Capacity/Production

70-MWe (net)

Coal

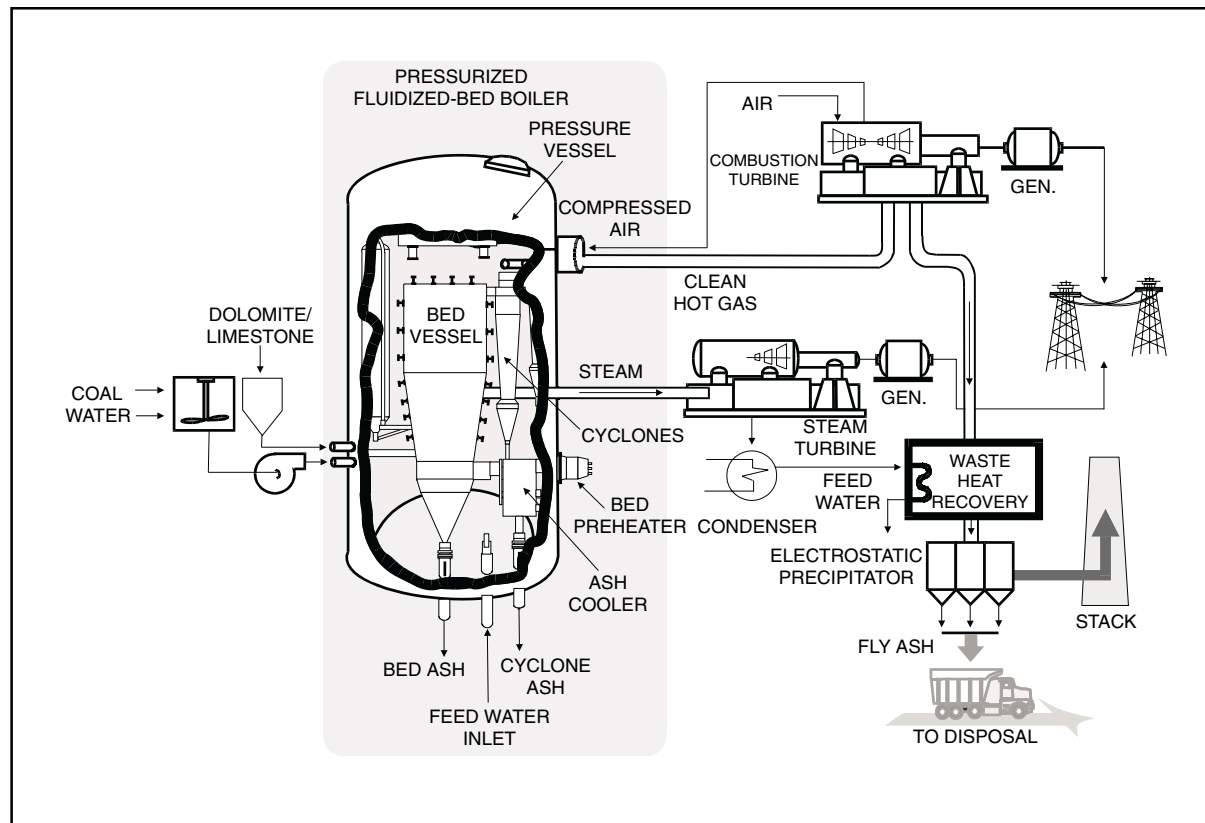
Ohio bituminous, 2–4% sulfur

Project Funding

Total project cost	\$189,886,339	100%
DOE	66,956,993	35
Participant	122,929,346	65

Project Objective

To verify expectations of PFBC economic, environmental, and technical performance in a combined-cycle repowering application at utility scale; and to accomplish greater than 90% SO₂ removal and NO_x emission level of 0.2 lb/10⁶ Btu at full load.



Technology/Project Description

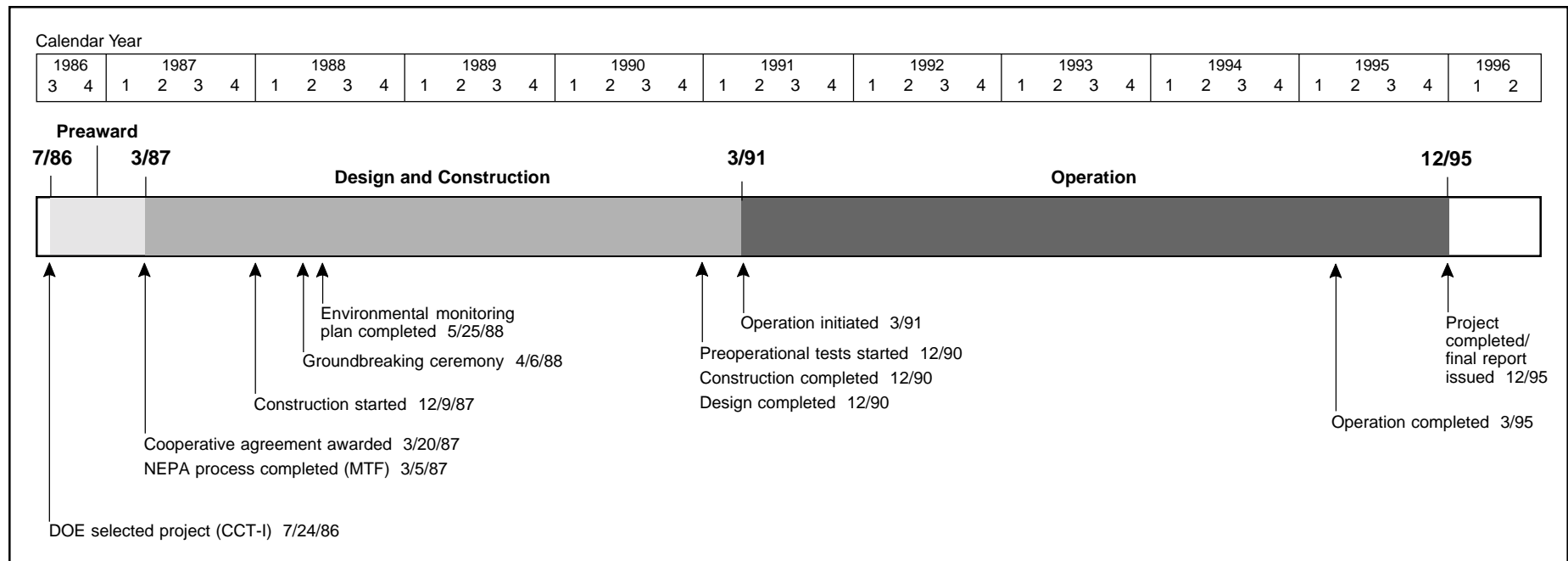
Tidd was the first large-scale operational demonstration of PFBC in the United States. The project represented a 13:1 scaleup from the pilot facility.

The boiler, cyclones, bed reinjection vessels, and associated hardware were encapsulated in a pressure vessel 45 feet in diameter and 70 feet high. The facility was designed so that one-seventh of the hot gases produced could be routed to an advanced particulate filter (APF).

The Tidd facility is a bubbling fluidized-bed combustion process operating at 12 atm (175 psi). Pressurized combustion air is supplied by the turbine compressor to fluidize the bed material, which consists of a coal-water fuel paste, coal ash, and a dolomite or limestone sorbent. Dolomite or limestone in the bed reacts with

sulfur to form calcium sulfate, a dry, granular bed-ash material, which is easily disposed of or is usable as a by-product. A low bed-temperature of about 1,600 °F limits NO_x formation.

The hot combustion gases exit the bed vessel with entrained ash particles, 98% of which are removed when the gases pass through cyclones. The cleaned gases are then expanded through a 15-MWe gas turbine. Heat from the gases exiting the turbine, combined with heat from a tube bundle in the fluid bed, generates steam to drive an existing 55-MWe steam turbine.



Results Summary

Environmental

- Sorbent size had the greatest effect on SO₂ removal efficiency as well as stabilization and heat transfer characteristics of the fluidized-bed.
- SO₂ removal efficiency of 90% was achieved at full load with a calcium-to-sulfur (Ca/S) molar ratio of 1.14 and temperature of 1,580 °F.
- SO₂ removal efficiency of 95% was achieved at full load with a Ca/S molar ratio of 1.5 and temperature of 1,580 °F.
- NO_x emissions were 0.15–0.33 lb/10⁶ Btu.
- CO emissions were less than 0.01 lb/10⁶ Btu.
- Particulate emissions were less than 0.02 lb/10⁶ Btu.

Operational

- Combustion efficiency ranged from an average 99.3% at low bed levels to an average 99.5% at moderate to full bed levels.
- Heat rate was 10,280 Btu/kWh (HHV, gross output) (33.2% efficiency) because the unit was small and no attempt was made to optimize heat recovery.
- An advanced particulate filter (APF), using a silicon carbide candle filter array, achieved 99.99% filtration efficiency on a mass basis.
- PFBC boiler demonstrated commercial readiness.
- ASEA Stal GT-35P gas turbine proved capable of operating commercially in a PFBC flue gas environment.

Economic

- The Tidd plant was a relatively small-scale facility, and as such, detailed economics were not prepared as part of this project.
- A recent cost estimate performed on Japan's 360-MWe PFBC Karita Plant projected a capital cost of \$1,263/kW (1997\$).

Project Summary

The Tidd PFBC technology is a bubbling fluidized-bed combustion process operating at 12 atmospheres (175 psi). Fluidized combustion is inherently efficient. A pressurized environment further enhances combustion efficiency, allowing very low temperatures that mitigate thermal NO_x generation, flue gas/sorbent reactions that increase sorbent utilization, and flue gas energy that is used to drive a gas turbine. The latter contributed significantly to system efficiency because of the high efficiency of gas turbines and the availability of gas turbine exhaust heat that can be applied to the steam cycle. A bed design temperature of 1,580 °F was established because it was the maximum allowable temperature at the gas turbine inlet and was well below temperatures for coal ash fusion, thermal NO_x formation, and alkali vaporization.

Coal crushed to one-quarter inch or less was injected into the combustor as a coal/water paste containing 25% water by weight. Crushed sorbent, either dolomite or limestone, was injected into the fluidized bed via two pneumatic feed lines, supplied from two lock hoppers. The sorbent feed system initially used two injector nozzles but was modified to add two more nozzles to enhance distribution.

In 1992, a 10-MWe equivalent APF was installed and commissioned as part of a research and development program and not part of the CCT Program demonstration. This system used ceramic candle filters to clean one-seventh of the exhaust gases from the PFBC system. The hot gas cleanup system unit replaced one of the seven secondary cyclones.

The Tidd PFBC demonstration plant accumulated 11,444 hours of coal-fired operations during its 54 months of operation. The unit completed 95 parametric tests, including continuous coal-fired runs of 28, 29, 30, 31, and 45 days. Ohio bituminous coals having sulfur contents of 2–4% were used in the demonstration.

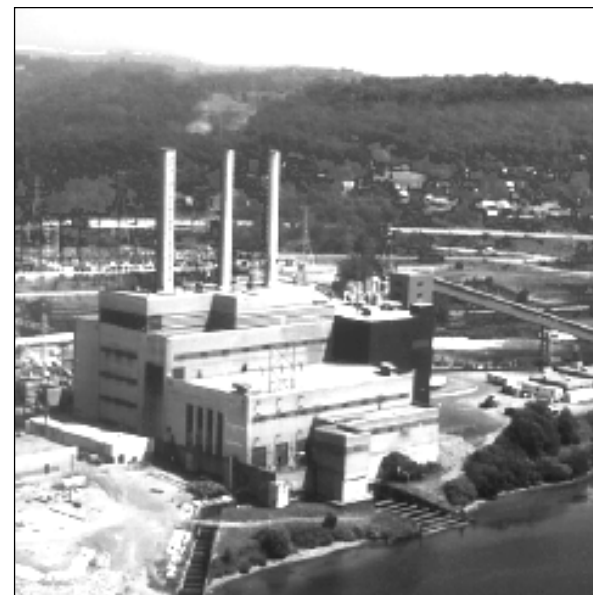
Environmental Performance

Testing showed that 90% SO_2 capture was achievable with a Ca/S molar ratio of 1.14 and that 95% SO_2 capture was possible with a Ca/S molar ratio of 1.5, provided the size gradation of the sorbent being utilized was optimized. This sulfur retention was achieved at a bed temperature of 1,580 °F and full bed height. Limestone induced deterioration of the fluidized-bed, and as a result, testing focused on dolomite. The testing showed that sulfur capture as well as sintering was sensitive to the fineness of the dolomite sorbent (Plum Run Greenfield dolomite was the design sorbent). Sintering of fluidized-bed materials, a fusing of the materials rather than effective reaction, had become a serious problem that required operation at bed temperatures below the optimum for effective boiler operation. Tests were conducted with sorbent size reduced from minus 6 mesh to a minus 12 mesh. The result with the finer material was a major positive impact on process performance without the expected excessive elutriation of sorbent. The finer material increased the fluidization activity as evidenced by a 10% improvement in heat transfer rate and an approximately 30% increase in sorbent utilization. In addition, the process was much more stable as indicated by reductions in temperature variations in both the bed and the evaporator tubes. Furthermore, sintering was effectively eliminated.

NO_x emissions ranged from 0.15–0.33 lb/10⁶ Btu, but were typically 0.2 lb/10⁶ Btu during the demonstration. These emissions were inherent to the process, which was operating at approximately 1,580 °F. No NO_x control enhancements, such as ammonia injection, were required. Emissions of carbon monoxide and particulates were less than 0.01 and 0.02 lb/10⁶ Btu, respectively.

Operational Performance

Except for localized erosion of the in-bed tube bundle and the more general erosion of the water walls, the Tidd boiler performed extremely well and was considered a commercially viable design. The in-bed tube bundle experienced no widespread erosion that would require



▲ The PFBC demonstration at the repowered 70-MWe unit at Ohio Power's Tidd Plant led to significant refinements and understanding of the technology.

significant maintenance. While the tube bundle experienced little wear, a significant amount of erosion on each of the four water walls was observed. This erosion posed no problem, however, because the area affected is not critical to heat transfer and could be protected by refractory.

The prototype gas turbine experienced structural problems and was the leading cause of unit unavailability during the first 3 years of operation. However, design changes instituted over the course of the demonstration proved effective in addressing the problem. The Tidd demonstration showed that a gas turbine could operate in a PFBC flue gas environment.

Efficiency of the PFBC combustion process was calculated during testing from the amount of unburned carbon in cyclone and bed ash, together with measurements of the amount of carbon monoxide in the flue gas. Combustion efficiencies averaged 99.5% at moderate to

full bed heights, surpassing the design or expected efficiency of 99.0%.

Using data for typical full-load operation, a heat rate of 10,280 Btu/kWh (HHV basis) was calculated. This corresponds to a cycle thermodynamic efficiency of 33.2% at a point where the cycle produced 70-MWe of gross electrical power while burning Pittsburgh No. 8 coal. Because the Tidd plant was a repowering application at a comparatively small scale, the measured efficiency does not represent what would be expected for a larger utility-scale plant using Tidd technology. Studies conducted under the PFBC Utility Demonstration Project showed that efficiencies of over 40% are likely for a larger utility-scale PFBC plant.

In summary, the Tidd project showed that the PFBC system could be applied to electric power generation. Further, the demonstration project led to significant refinements and understanding of the technology in the areas of turbine design, sorbent utilization, sintering, post-bed combustion, ash removal, and boiler materials.

Testing of the APF for over 5,800 hours of coal-fired operation showed that the APF vessel was structurally adequate; the clay-bonded silicon carbide candle filters were structurally adequate unless subjected to side loads from ash bridging or buildup in the vessel; bridging was precluded with larger particulates included in the particulate matter; and filtration efficiency (mass basis) was 99.99%.

Economic Performance

The Tidd plant was a relatively small-scale demonstration facility, so detailed economics were not prepared as part of this project. However, a recent cost estimate performed on Japan's 360-MWe PFBC Karita Plant projected a capital cost of \$1,263/kW (1997\$).

Commercial Applications

Combined-cycle PFBC permits use of a wide range of coals, including high-sulfur coals. The compactness of bubbling-bed PFBC technology allows utilities to significantly increase capacity at existing sites. Compactness of

the process due to pressurized operation reduces space requirements per unit of energy generated. PFBC technology appears to be best suited for applications of 50 MWe or larger. Capable of being constructed modularly, PFBC generating plants permit utilities to add increments of capacity economically to match load growth. Plant life can be extended by repowering with PFBC using the existing plant area, coal- and waste-handling equipment, and steam turbine equipment.

The 360-MWe Karita Plant in Japan, which uses ABB Carbon P800 technology, represents a major move toward commercialization of PFBC bubbling-bed technology. A second generation P200 PFBC is under construction in Germany. Other PFBC projects are under consideration in China, South Korea, the United Kingdom, Italy, and Israel.

The Tidd project received *Power* magazine's 1991 Powerplant Award. In 1992, the project received the National Energy Resource Organization award for demonstrating energy efficient technology.

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References

- *Tidd PFBC Hot Gas Cleanup Program Final Report*. Report No. DOE/MC/26042-5130. The Ohio Power Company. October 1995. (Available from NTIS as DE96000650.)
- *Tidd PFBC Demonstration Project Final Report, Including Fourth Year of Operation*. The Ohio Power Company. August 1995. (Available from DOE Library/Morgantown, 1-800-432-8330, ext. 4184 as

DE96000623.)

- *Tidd PFBC Demonstration Project Final Report, March 1, 1994–March 30, 1995*. Report No. DOE/MC/24132-T8. The Ohio Power Company. August 1995. (Available from NTIS as DE96004973.)
- *Tidd PFBC Demonstration Project—First Three Years of Operation*. Report No. DOE/MC/24132-5037-Vol. 1 and 2. The Ohio Power Company. April 1995. (Available from NTIS as DE96000559 for Vol. 1 and DE96003781 for vol. 2.)



▲ Coal and sorbent conveyors can be seen just after entering the Tidd plant.

Nucla CFB Demonstration Project

Project completed.

Participant

Tri-State Generation and Transmission Association, Inc.

Additional Team Members

Foster Wheeler Energy Corporation*—technology supplier

Technical Advisory Group (potential users)—cofunder

Electric Power Research Institute—technical consultant

Location

Nucla, Montrose County, CO (Nucla Station)

Technology

Foster Wheeler's atmospheric circulating fluidized-bed (ACFB) combustion system

Plant Capacity/Production

100-MWe (net)

Coal

Western bituminous—

Salt Creek, 0.5% sulfur, 17% ash

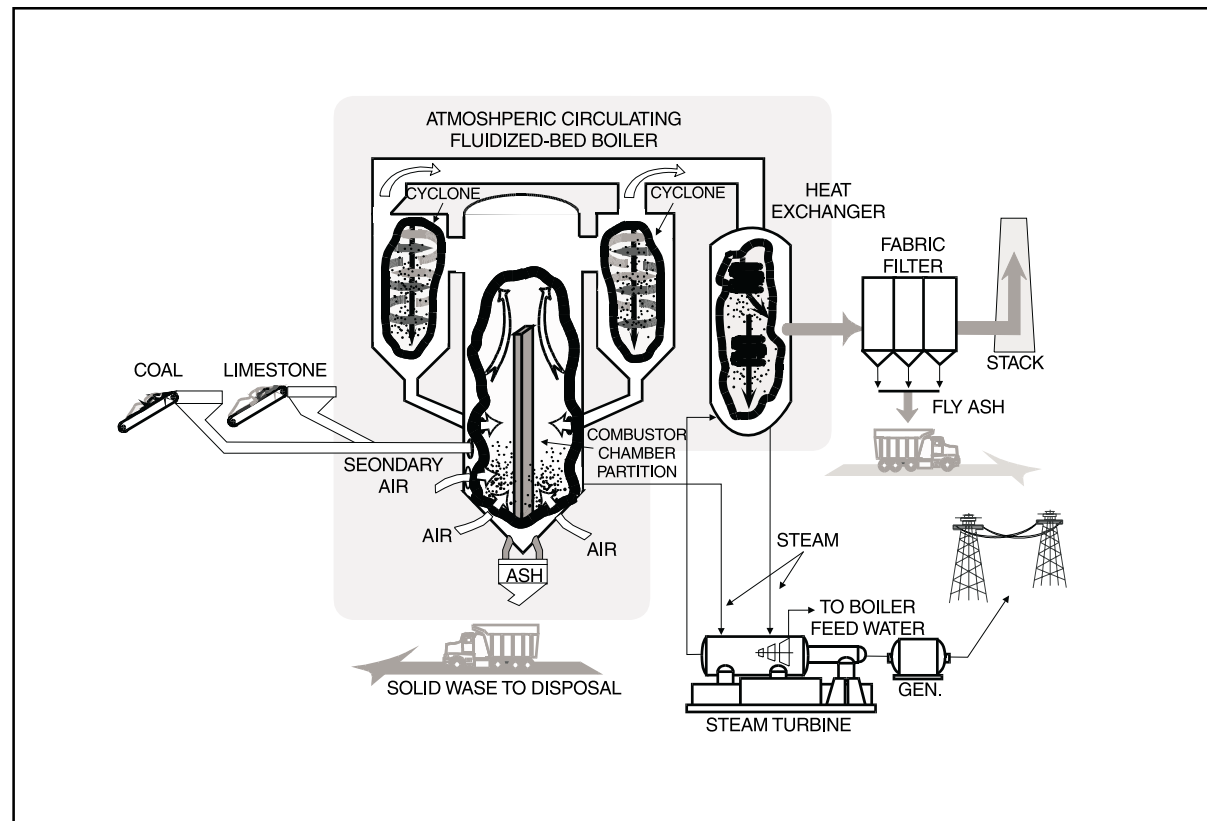
Peabody, 0.7% sulfur, 18% ash

Dorchester, 1.5% sulfur, 23% ash

Project Funding

Total project cost	\$160,049,949	100%
DOE	17,130,411	11
Participant	142,919,538	89

*Pyropower Corporation, the original technology developer and supplier, was acquired by Foster Wheeler Energy Corp.



Project Objective

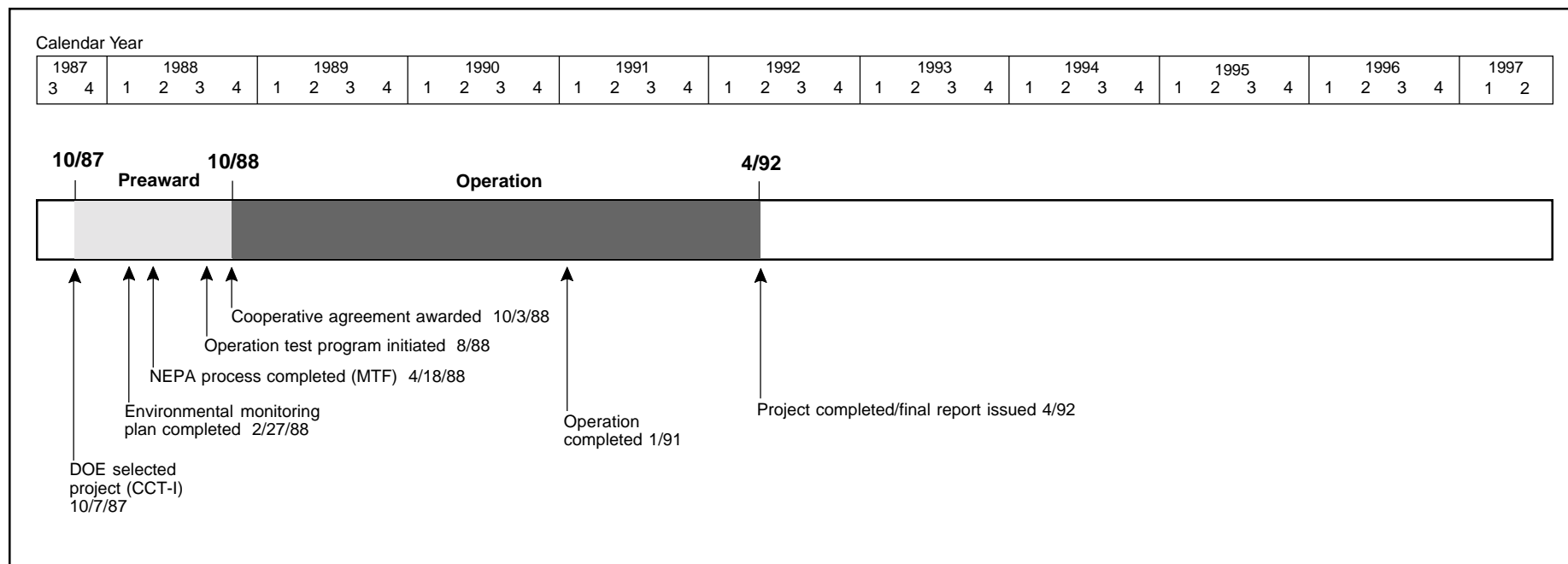
To demonstrate the feasibility of ACFB technology at utility scale and to evaluate the economic, environmental, and operational performance at that scale.

Technology/Project Description

Nucla's circulating fluidized-bed system operates at atmospheric pressure. In the combustion chamber, a stream of air fluidizes and entrains a bed of coal, coal ash, and sorbent (e.g., limestone). Relatively low combustion temperatures limit NO_x formation. Calcium in the sorbent combines with SO_2 gas to form calcium sulfite and sulfate solids, and solids exit the combustion chamber and flow into a hot cyclone. The cyclone separates the solids from the gases, and the solids are recycled for combustor temperature control. Continuous circulation of coal and sor-

bent improves mixing and extends the contact time of solids and gases, thus promoting high utilization of the coal and high-sulfur-capture efficiency. Heat in the flue gas exiting the hot cyclone is recovered in the economizer. Flue gas passes through a baghouse where particulate matter is removed. Steam generated in the ACFB is used to produce electric power.

Three small, coal-fired, stoker-type boilers at Nucla Station were replaced with a new 925,000-lb/hr ACFB steam generator capable of driving a new 74-MWe turbine generator. Extraction steam from this turbine generator powers three existing turbine generators (12-MWe each).



Results Summary

Environmental

- Bed temperature had the greatest effect on pollutant emissions and boiler efficiency.
- At bed temperatures below 1,620 °F, sulfur capture efficiencies of 70 and 95% were achieved at calcium-to-sulfur (Ca/S) molar ratios of 1.5 and 4.0, respectively.
- During all tests, NO_x emissions averaged 0.18 lb/10⁶ Btu and did not exceed 0.34 lb/10⁶ Btu.
- CO emissions ranged from 70–140 ppmv.
- Particulate emissions ranged from 0.0072–0.0125 lb/10⁶ Btu, corresponding to a removal efficiency of 99.9%.
- Solid waste was essentially benign and showed potential as an agricultural soil amendment, soil/roadbed stabilizer, or landfill cap.

Operational

- Boiler efficiency ranged from 85.6–88.6% and combustion efficiency ranged from 96.9–98.9%.
- A 3:1 boiler turndown capability was demonstrated.
- Heat rate at full load was 11,600 Btu/kWh and was 12,400 Btu/kWh at half load.

Economic

- Capital cost for the Nucla retrofit was \$1,123/kW and a normalized power production cost was 64 mills/kWh.

Project Summary

Fluidized-bed combustion evolved from efforts to find a combustion process conducive to controlling pollutant emissions without external controls. Fluidized-bed combustion enables efficient combustion at temperatures of 1,400–1,700 °F, well below the thermal NO_x formation temperature (2,500 °F), and enables high SO_2 -capture efficiency through effective sorbent/flue gas contact. ACFB differs from the more traditional fluid-bed combustion. Rather than submerging a heat exchanger in the fluid bed, which dictates a low-fluidization velocity, ACFB uses a relatively high fluidization velocity, which entrains the bed material. Hot cyclones capture and return the solids emerging from the turbulent bed to control temperature and extend the gas/solid contact time and to protect a downstream heat exchanger.

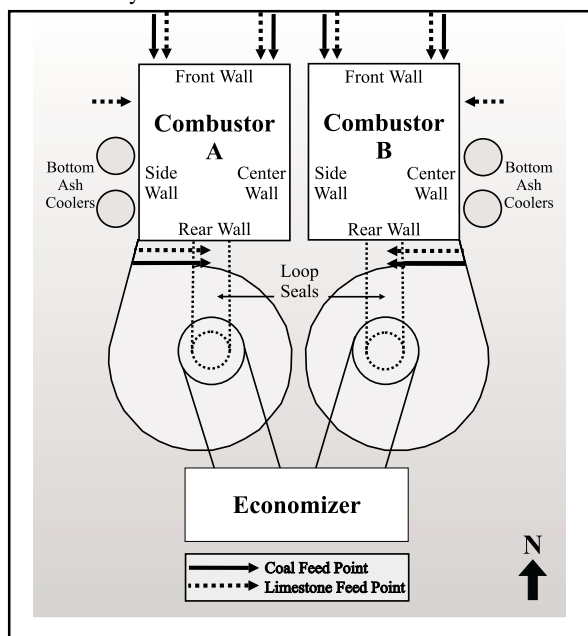
Interest and participation of DOE, EPRI, and the Technical Advisory Group (potential users) resulted in the evaluation of ACFB potential for broad utility application through a comprehensive test program. Over a two-and-a-half-year period, 72 steady-state performance tests were conducted and 15,700 hours logged. The result was a database that remains the most comprehensive, available resource on ACFB technology.

Operational Performance

Between July 1988 and January 1991, the plant operated with an average availability of 58% and an average capacity factor of 40%. However, toward the end of the demonstration, most of the technical problems had been overcome. During the last three months of the demonstration, average availability was 97% and the capacity factor was 66.5%.

Over the range of operating temperature at which testing was performed, bed temperature was found to be the most influential operating parameter. With the exception of coal-fired configuration and excess air at elevated temperatures, bed temperature was the only parameter that had a measurable impact on emissions and efficiency.

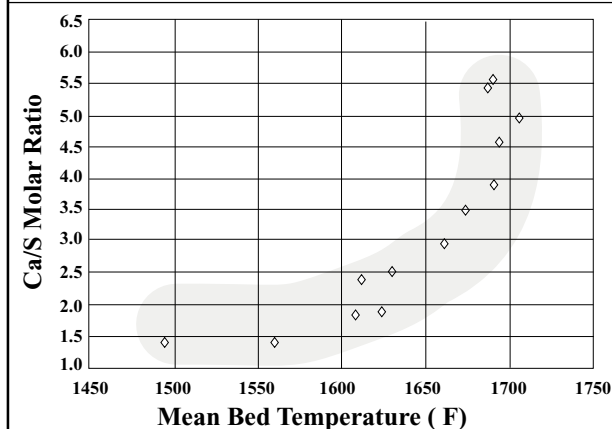
▼ Plant layout with coal and limestone feed locations.



Combustion efficiency, a measure of the quantity of carbon that is fully oxidized to CO_2 , ranged from 96.9–98.9%. Of the four exit sources of incompletely burned carbon, the largest was carbon contained in the fly ash (93%). The next largest (5%) was carbon contained in the bottom ash stream, and the remaining feed-carbon loss (2%) was incompletely oxidized CO in the flue gas. The fourth possible source, hydrocarbons in the flue gas, was measured and found to be negligible.

Boiler efficiencies for 68 performance tests varied from 85.6–88.6%. The contributions to boiler heat loss were identified as unburned carbon, sensible heat in dry flue gas, fuel and sorbent moisture, latent heat in burning hydrogen, sorbent calcination, radiation and convection, and bottom-ash cooling water. Net plant heat rate decreased with increasing boiler load, from 12,400 Btu/kWh at 50% of full load to 11,600 Btu/kWh at full load. The lowest value achieved during a full-load steady-state test was 10,980 Btu/kWh. These values were affected by the

Exhibit 5-40
Effect of Bed Temperature
on Ca/S Requirement



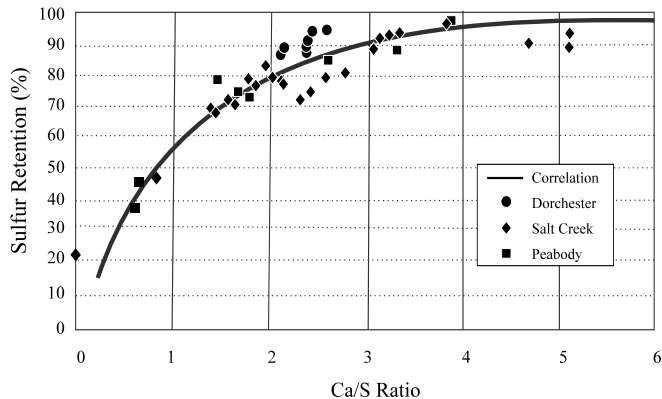
absence of reheat, the presence of the three older 12.5-MWe turbines in the overall steam cycle, the number of unit restarts, and part-load testing.

Environmental Performance

As indicated above, bed temperature had the greatest impact on ACFB performance, including pollutant emissions. Exhibit 5-40 shows the effect of bed temperatures on the Ca/S molar ratio requirement for 70% sulfur retention. The Ca/S molar ratios were calculated based on the calcium content of the sorbent only, and do not account for the calcium content of the coal. While a Ca/S molar ratio of about 1.5 was sufficient to achieve 70% sulfur retention in the 1,500–1,620 °F range, the Ca/S molar ratio requirement jumped to 5.0 or more at 1,700 °F or greater.

Exhibit 5-41 shows the effect of Ca/S molar ratio on sulfur retention at average bed temperatures below 1,620 °F. Salt Creek and Peabody coals contain 0.5% and 0.7% sulfur, respectively. To achieve 70% SO_2 reduction, or the 0.4 lb/10⁶ Btu emission rate required by the licensing

Exhibit 5-41 Calcium Requirements and Sulfur Retentions for Various Fuels



agreement, a Ca/S molar ratio of approximately 1.5 is required. To achieve an SO₂ reduction of 95%, a Ca/S molar ratio of approximately 4.0 is necessary. Dorchester coal, averaging 1.5% sulfur content, required a somewhat lower Ca/S molar ratio for a given reduction.

NO_x emissions measured throughout the demonstration were less than 0.34 lb/10⁶ Btu, which is well below the regulated value of 0.5 lb/10⁶ Btu. The average level of NO_x emissions for all tests was 0.18 lb/10⁶ Btu. NO_x emissions indicate a relatively strong correlation with temperature, increasing from 40 ppmv (0.06 lb/10⁶ Btu) at 1,425 °F to 240 ppmv (0.34 lb/10⁶ Btu) at 1,700 °F. Limestone feed rate was also identified as a variable affecting NO_x emissions, *i.e.*, somewhat higher NO_x emissions resulted from increasing calcium-to-nitrogen (Ca/N) molar ratios. The mechanism was believed to be oxidation of volatile nitrogen in the form of ammonia (NH₃) catalyzed by calcium oxide. CO emissions decrease as temperature increases, from 140 ppmv at 1,425 °F to 70 ppmv at 1,700 °F.

At full load, the hot cyclones removed 99.8% of the particulates. With the addition of baghouses, removal efficiencies achieved on Peabody and Salt Creek Coals were 99.905% and 99.959%, respectively. This equated to emission levels of 0.0125 lb/10⁶ Btu for Peabody coal and 0.0072 lb/10⁶ Btu for Salt Creek coal, well below the required 0.03 lb/10⁶ Btu.

Economic Performance

The final capital costs associated with the engineering, construction, and startup of the Nucla ACFB system were \$112.3 million. This represents a cost of \$1,123/kW (net). Total power costs associated with plant operations between September 1988 and January 1991 were approximately \$54.7 million, resulting in a normalized cost of power production of 64 mills/kWh. The average monthly operating cost over this period was about \$1,888,000. Fixed costs represent about 62% of the total and include interest (47%), taxes (4.8%), depreciation (6.9%), and insurance (2.7%). Variable costs represent more than 38% of the power production costs and include fuel expenses (26.2%), non-fuel expenses (6.8%), and maintenance expenses (5.5%).

Commercial Applications

The Nucla project represented the first repowering of a U.S. utility plant with ACFB technology and showed the technology's effectiveness to burn a wide variety of coals cleanly and efficiently. The comprehensive database resulting from the Nucla project enabled the resultant technology to be replicated in numerous commercial plants throughout the world. Nucla continues in commercial service.

Today, every major boiler manufacturer offers an ACFB system in its product line. There are now more

than 120 fluidized-bed combustion boilers of varying capacity operating in the U.S. and the technology has made significant market penetration abroad. The fuel flexibility and ease of operation make it a particularly attractive power generation option for the burgeoning power market in developing countries.

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References

- *Colorado-Ute Nucla Station Circulating Fluidized-Bed (CFB) Demonstration—Volume 2: Test Program Results*. EPRI Report No. GS-7483. October 1991.
- *Demonstration Program Performance Test: Summary Reports*. Report No. DOE/MC/25137-3104. Colorado-Ute Electric Association, Inc. March 1992. (Available from NTIS as DE92001299.)
- *Economic Evaluation Report: Topical Report*. Report No. DOE/MC/25137-3127. Colorado-Ute Electric Association, Inc., March 1992. (Available from NTIS as DE93000212.)
- *Nucla CFB Demonstration Project: Detailed Public Design Report*. Report No. DOE/MC/25137-2999. Colorado-Ute Electric Association, Inc., December 1990. (Available from NTIS as DE91002081.)

